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Choice of display phosphors: a theoretical study of the colorimetric consequences

No. 1971/2

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

CHOICE OF DISPLAY PHOSPHORS: A THEORETICAL STUDY OF THE COLORIMETRIC CONSEQUENCES

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D.Maurice

W.N. Sproson, M.A. (Cantab.), F.Inst.P.

Head of Research Department

(PH-67)

Foreword

This report sets out to give a quantitative colorimetric basis to the various observations and experiments described in the companion BBC Research Department Report 1970/32 'The Choice of Primary Colours for Colour Television' and it is preferably read in conjunction with that report. In particular little or no general explanation of elementary colorimetric principles is given; furthermore, the full implications of the various possible phosphor choices are dealt with comprehensively in Report 1970/32 and are therefore not considered in detail here.

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CHOICE OF DISPLAY PHOSPHORS: A THEORETICAL STUDY OF THE COLORIMETRIC CONSEQUENCES

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Summary

Modern colour cameras (and telecine machines) use an electrical matrix to approximate the effect of negative lobes, which are required for ideal colour analysis. By this means much better colour reproduction is now possible than was formerly the case. There is a penalty, however, in that the analysis must match (i.e. be designed for) a specific set of phosphors in the colour display tube. This report analyses the effects of slight departures from the design set of phosphors such as are encountered in presently available colour television receivers and it also considers the colour reproduction given by cameras designed for the original NTSC set of phosphors. It is concluded that slight changes in chromaticity coordinates are permissible but the colour quality obtainable from a camera designed for the NTSC primaries is very unlikely to be acceptable.

1. Introduction

The ideal spectral responses of the red, green and blue channels of a 3-tube colour camera* are primarily determined by the chromaticities of the display phosphors and each channel (Fig. 1) characteristic has a major positive response and two subsidiary regions. For the green channel the subsidiary regions are both negative, for the red channel there is a substantial negative region (peak at about 510 to 520 nm) and a small positive region in the blue part of the spectrum, and the blue channel has a subsidiary negative region in the green and a very small (usually negligible in practical terms) region in the red which may be positive or negative.

The ideal analysis characteristics enable objectively accurate colour reproduction to be achieved for all physically realisable colours i.e. all colours having chromaticity co-ordinates within the colour triangle defined by the phosphor primaries; the objectively accurate colour reproduction is a metameric match (not a spectral power match) but this feature is common to all modern colour reproduction processes.

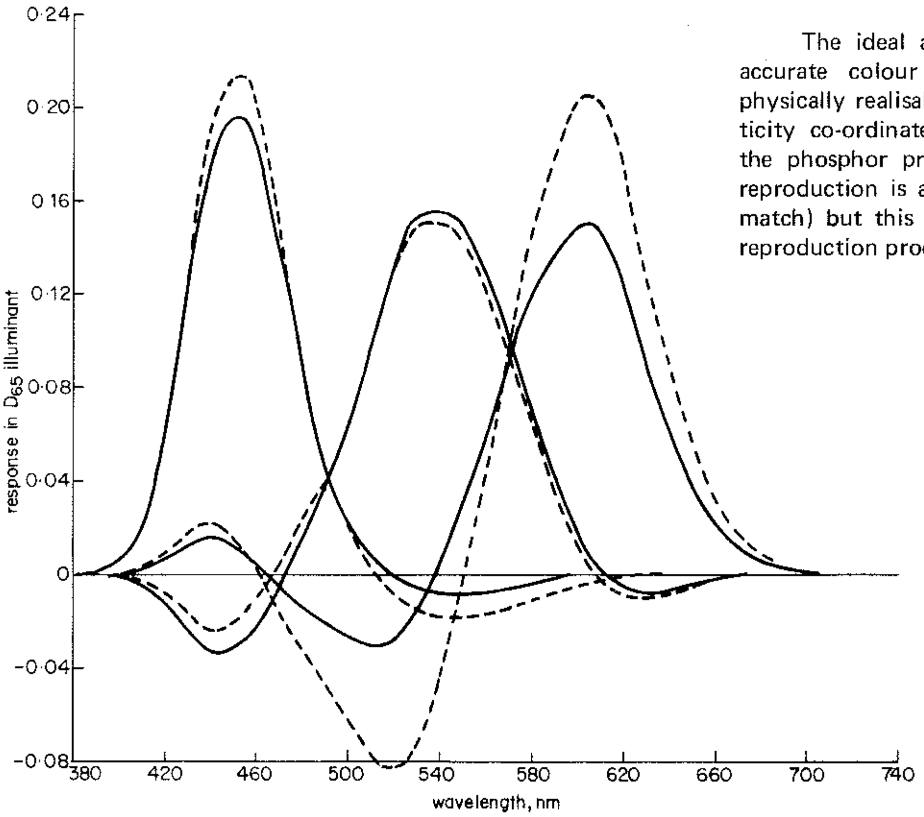

Fig. 1 - Ideal analysis

—— NTSC Primaries
----- System I Primaries

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* The case of a 4-tube camera is in some ways similar to that of a 3-tube camera but there are additional complications: the colouring channels closely resemble the *RGB* channels of the 3-tube camera but the choice of *l*, *m*, *n* coefficients to form the unity-gamma low-bandwidth luminance signal is a function of the display phosphor characteristic. It has been thought better to restrict this report to a consideration of a 3-tube camera because it is more fundamental in terms of basic colorimetric considerations.

The ability to phase invert electrical signals and hence to produce negative lobes in the spectral sensitivity curves of a colour camera was realised at least twenty years ago but it was not until the invention of the plumbicon camera tube that it became practicable to apply this idea. The two most important features of the plumbicon tube for this purpose were (i) a signal-to-noise ratio, using a well designed head amplifier, well in excess of minimum requirements (i.e. in excess of 40 dB) (ii) a linear transfer characteristic.

Prior to the advent of the plumbicon tube, it was usual to use spectral sensitivity characteristics which were an approximation to the major positive lobes of the ideal curves. The absence of negative lobes was partially compensated by making the analysis curves slightly narrower so that the overlaps between the curves were rather less but the crossover wavelengths (at which the green and red channels have the same sensitivity, on the one hand, and the blue and green channels have the same sensitivity, on the other hand) were kept constant. In the situation where only the major positive lobes are used, a change in the chromaticities of the display phosphors has relatively little effect on the optimum colorimetric analysis and no special attention to the camera analysis is needed if the display phosphors are changed.

Within the past three or four years it has become usual to apply a 3 x 3 matrix to the RGB linear output of the 3-tube colour camera* and in this way better colour pictures have been produced because the analysis is a much better approximation to the ideal analysis than was previously possible. This improvement in colour quality is achieved with two consequences (i) a slight loss of signal-to-noise ratio in the displayed pictures because noise power is added when signals are subtracted (ii) the need to adhere fairly closely to the phosphor chromaticities for which the 3 x 3 matrix was computed. If the second feature is ignored and the colour display is not the intended one, the matrix may impair the pictures and produce a colorimetrically less pleasing picture than if no matrix were used. The reason for this is that a change of phosphor primaries has a very considerable effect on the shapes and positions of the subsidiary lobes (negative and positive) although, as noted above, relatively little effect on the shapes of the main lobes. This matter will be dealt with quantitatively in the next section.

2. Ideal colour analysis

The ideal colour analysis characteristics are derived from:

(1) The chromaticity co-ordinates of the R, G and B display primaries
(2) The chosen white point e.g. D_{65}

together with fundamental data about the colour matching characteristic of the average human eye (1931 CIE standard observer). For the NTSC primaries[1] the quantitative relation is expressed most conveniently by the matrix equation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1{\cdot}972 & -0{\cdot}549 & -0{\cdot}297 \\ -0{\cdot}954 & 1{\cdot}936 & -0{\cdot}027 \\ 0{\cdot}063 & -0{\cdot}129 & 0{\cdot}981 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

This equation gives values of RGB outputs (in linear signal condition) necessary to match (using a hypothetical unity-gamma tube) any colour whose XYZ tristimulus values are known. If the XYZ values are made to take the values appropriate to spectrum colours of wavelength 380 to 770 nm at (say) intervals of 10 nm, the ideal analysis curves are obtained. Fig. 1 shows the result of this computation and includes the effect of the incident illuminant (D_{65}) thus making the three curves of equal area.*

No practical camera has been given exactly these sensitivity curves because more than 3 sensors would be required (9 for perfect agreement, apart from an XYZ analysis) but a very reasonable approximation to this set of curves can be achieved with a practical 3-tube camera and a suitably computed 3 x 3 matrix (see Section 3).

A camera designed to match the System I display primaries[1] has ideal analysis curves given by matrix Equation (2)

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3{\cdot}073 & -1{\cdot}403 & -0{\cdot}475 \\ -0{\cdot}970 & 1{\cdot}877 & 0{\cdot}042 \\ 0{\cdot}074 & -0{\cdot}235 & 1{\cdot}068 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (2)$$

The result of substituting the XYZ values of the spectrum colours and additionally including the spectrum of the illuminant (D_{65}) is also shown in Fig. 1 (dashed lines). It will be observed that the subsidiary lobes of the two sets of curves (NTSC and System I) are appreciably different and the most important parameters have been summarised in Table 1.

3. Colour analysis of a practical camera

The limitation of 3 tubes (or 3 colouring tubes in a 4-tube camera) implies that, at best, a good approximation to the ideal curves is the most that can be achieved in a practical camera using a 3 x 3 matrix. Fig. 2 shows the extent to which a real camera can approximate to the ideal analysis for a camera designed to match the NTSC primaries. The negative lobe of the green channel response in the blue part of the spectrum and the negative lobe of the blue channel in the green are both fairly good approximations to the ideal. The least satisfactory feature is the negative green part of the red channel response which occurs at the wrong wavelength (peak at 530 nm instead of 512 nm) and is given a low amplitude because of the wavelength mismatch. The wavelength mismatch is inevitable because this negative lobe is achieved by phase

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* Linear matrices have also been applied to the colouring channels of a 4-tube camera but this case will not be discussed for the reasons already stated (in the first footnote).

* If the camera sensitivities to equi-energy illuminant are plotted the areas are not equal but in the ratio 1·126 : 0·955 : 0·915. Multiplication by D_{65} makes the ratio 1 : 1 : 1.

TABLE 1

Comparison of Ideal Analysis for Two Sets of Phosphors

	wavelengths of peaks			Positive Crossovers				Principal Negative Sensitivities					
	λ_R nm	λ_G nm	λ_B nm	λ_{BG} nm	amplitude	λ_{GR} nm	amplitude	λ_{BG} of neg. red nm	amplitude	λ_G of neg. blue nm	amplitude	λ_B of neg. green nm	amplitude
NTSC	603	534	452	492	·042	572	·095	512	−·032	550	−·090	444	−·034
System I	604	535	452	492	·043	570	·092	520	−·084	550	−·190	443	−·024

inverting and attenuating the output from the green channel (peak 535 nm). In spite of these deficiencies the colorimetric performance of this camera is computed * to be very good when feeding a monitor with NTSC phosphor primaries.

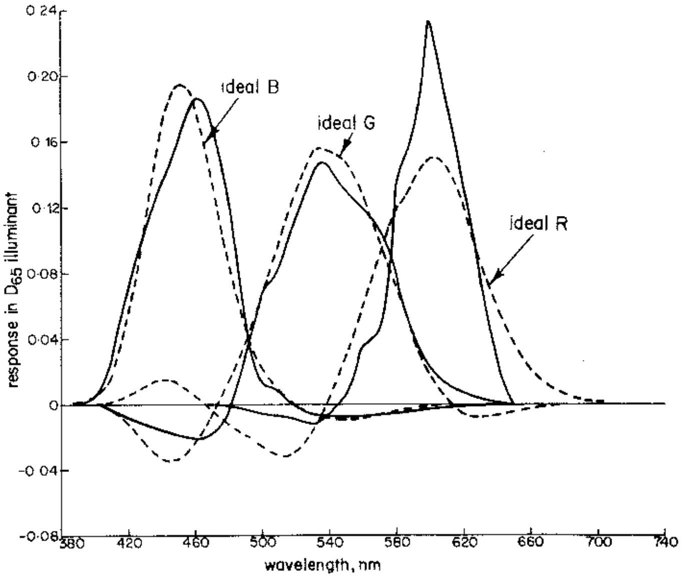

Fig. 2 - Effective analysis of a camera designed for NTSC ideal analysis for NTSC primaries is also shown

The analysis characteristics of a 3-tube camera with a matrix computed to suit System I phosphors are shown in Fig. 3 together with the ideal characteristics. Again there is a lack of precise matching of the subsidiary lobes. The negative lobe of the red channel has increased (ref. the NTSC camera) and is perhaps more closely followed but the small positive lobe (in the blue region) is given a slight negative value by the computer optimisation programme used to determine the coefficients of the 3 x 3 matrix.[2] The negative lobe of the blue channel is closely followed. The negative lobes of the green channel are very imperfectly followed in that the short wavelength one is given less than half the correct amplitude (with some wavelength mismatch) and no attempt is made to follow the negative lobe with a peak wavelength of 630 nm. Despite these imperfections, the computed and observed colorimetric performance of this camera with a monitor having the System I display phosphors is fairly good. For the standard 26 test colours[2] which have now been used for many colorimetric studies the average chromaticity error is 3·1 j.n.d. and the luminance error 1·8 j.n.d. The corresponding figures for the NTSC phosphor display used with the 'NTSC camera' is 2·9 j.n.d.'s chromaticity error and 1·9 luminance error. The slightly lower figure for the chromaticity error is due to the larger gamut of colours given by the NTSC phosphors. Within the area on the chromaticity diagram common to both sets of phosphors the reproductions are identical.

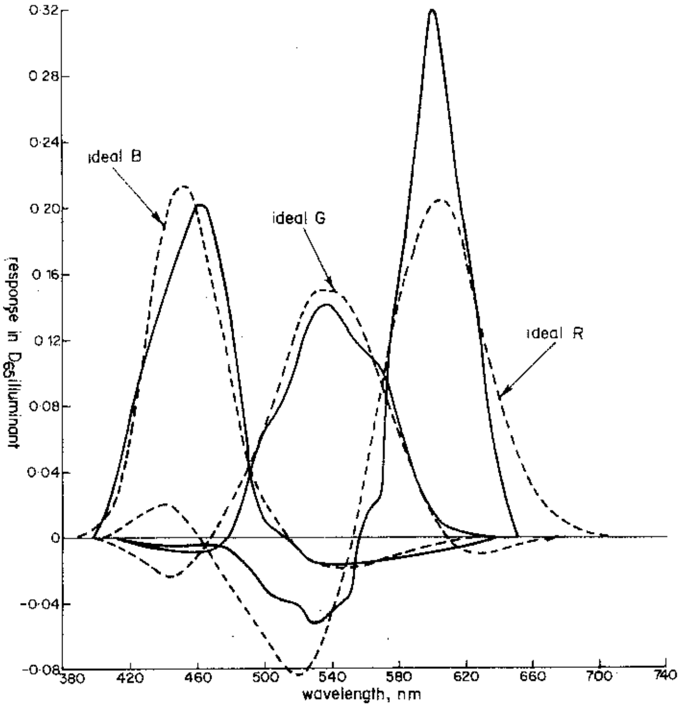

Fig. 3 - Effective analysis of a camera designed for System I ideal analysis for System I primaries is also shown

The derivation of analysis characteristics, the computation of the optimum 3 x 3 matrix and the computation of colour and luminance errors discussed so far have assumed an overall transfer characteristic (from scene to display monitor) of unity-gamma. It is normal practice to use a gamma-correction law in the camera of index 0·45 and the display monitor has a typical gamma of index 2·8. This gives an overall gamma of 1·26. The effect of this departure from unity-gamma will be considered in Section 5.

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* Since monitors with NTSC phosphors no longer exist, computation is the only means of assessing this camera and monitor combination.

TABLE 2

	Red		Green		Blue	
	x	y	x	y	x	y
System I	0·64	0·33	0·29	0·60	0·15	0·06
'69 – '70 current phosphors	0·632	0·339	0·307	0·597	0·152	0·064
'70 – '71 complementary shift phosphors	0·627	0·341	0·325	0·590	0·150	0·060
	u	v	u	v	u	v
System I	0·451	0·349	0·121	0·374	0·175	0·105
'69 – '70 current phosphors	0·436	0·350	0·129	0·375	0·176	0·111
'70 – '71 complementary shift phosphors	0·430	0·350	0·138	0·375	0·175	0·105

4. Effects of mismatch between camera and display monitor ($\gamma = 1$)

4.1. Camera designed for PAL System I: display on three sets of phosphors

There is a constant search for improved and better phosphors, usually with a view to producing a brighter picture and it has to be acknowledged that in terms of presently available display tubes there are some variations of chromaticity co-ordinates. These have been classified by Wood[3] into (i) System I phosphors (ii) '69 – '70 current phosphors (iii) '70 – '71 complementary shift phosphors.

The chromaticity co-ordinates of these three sets of phosphors are given in Table 2 and plotted on the 1960 CIE – UCS diagram in Fig. 4.

The effect of using a camera designed for PAL System I with the above three sets of phosphors has been computed for the 26 test colours and two of the groups into which these colours may be classified; the results are summarised in Table 3.

TABLE 3

	System I		'69 – '70 Current Phosphors		'69 – '70 Complementary Shift Phosphors	
	Chromaticity errors	Luminance errors	Chromaticity errors	Luminance errors	Chromaticity errors	Luminance errors
	j.n.d.	j.n.d.	j.n.d.	j.n.d.	j.n.d.	j.n.d.
All Colours	3·1	1·8	4·1	1·7	4·8	0·9
Flesh Tones	1·1	0·5	1·6	0·3	2·2	0·2
Saturated Colours	6·3	3·9	8·0	3·7	9·2	2·1

Although Table 3 shows less errors for flesh tones than for the other groups of colours, it is known that observers are much more sensitive to changes in flesh tones[3] and for this reason, five of the flesh tones have been plotted on the 1960 CIE – UCS chromaticity diagram (Fig. 5).

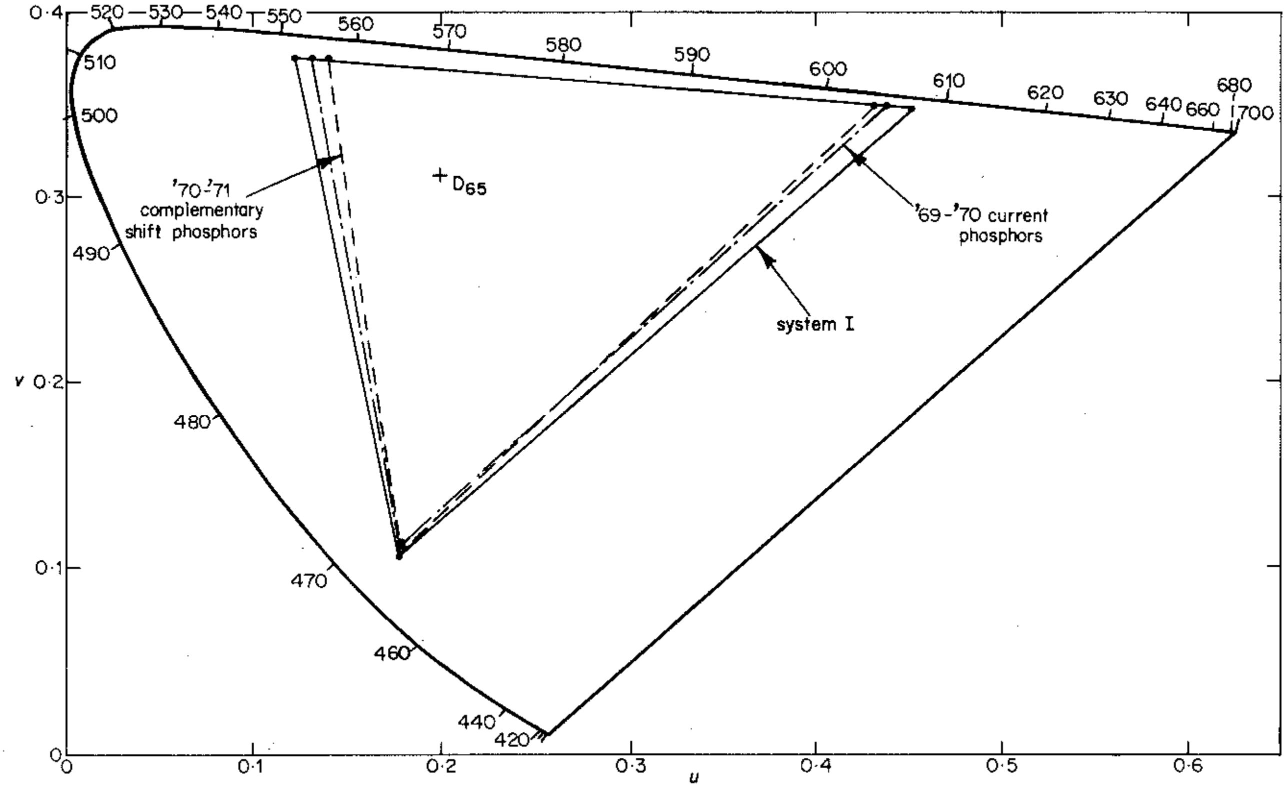

Fig. 4 - Chromaticity coordinates and colour gamuts of three sets of phosphors

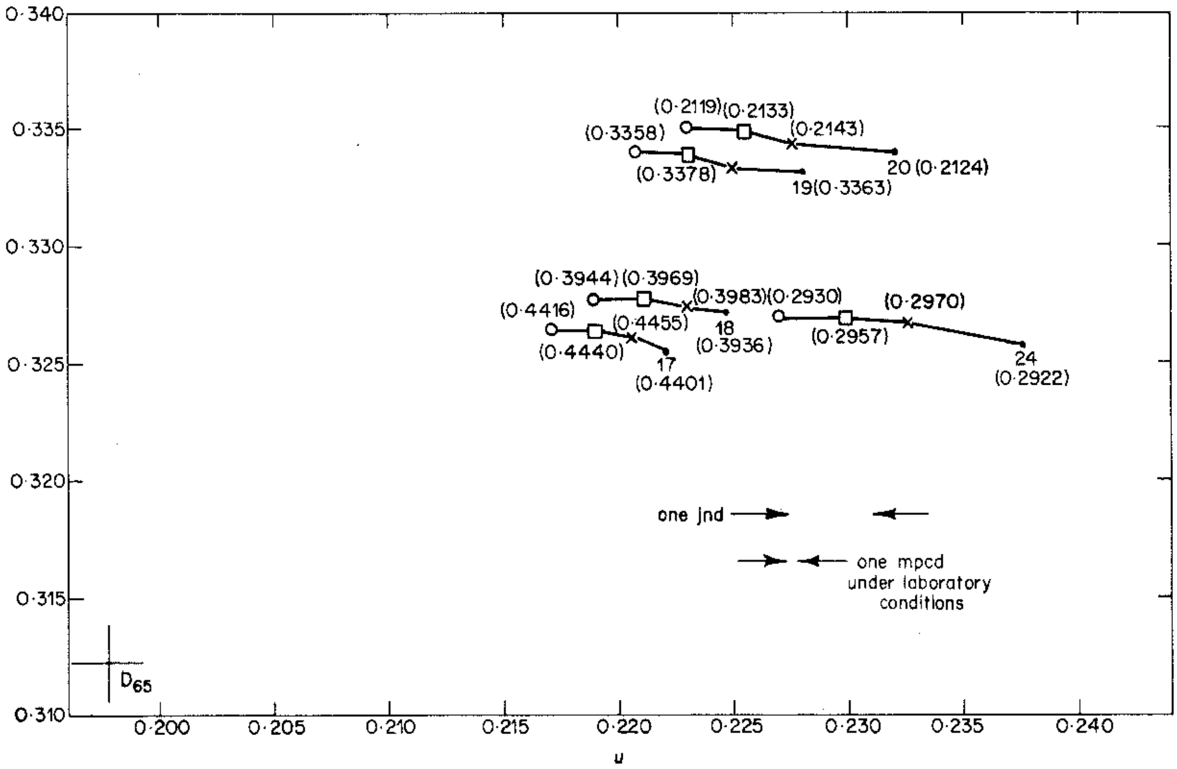

Fig. 5 - Camera designed for System I: Flesh tones (Nos. 17, 18, 19, 20 and 24) displayed on three sets of phosphors. γ = 1

● Original chromaticity X Chromaticity of System I display O Chromaticity of '70 – '71 complementary shift phosphor display
□ Chromaticity of '69 – '70 current phosphor display Numbers in brackets are relative luminance

The magnitude of the chromaticity j.n.d. chosen in this report and other BBC Research Department Reports dealing with colorimetry is shown graphically in Fig. 5 and has a magnitude of 0·00384 units on the 1960 CIE – UCS diagram. It should be pointed out that this is intended to represent a just noticeable difference under the viewing conditions which generally apply to colour television where judgements are often made on a memory or plausibility basis. Under the best laboratory conditions* much smaller colour differences can be perceived and the magnitude of the minimum perceptible colour difference (m.p.c.d.) is about 0·0004 which is also shown in Fig. 5. The larger unit (j.n.d.) is thought to be more realistic for most colour television judgements, but it is realised that circumstances can arise where the j.n.d. is rather large and should not be too literally interpreted as a just noticeable difference. The size of the luminance j.n.d. is based on a 2% difference in luminance between adjacent identical colours (or neutrals). This is approximately correct at the higher end of the luminance range but is too small a unit for dark greys and near blacks. As pointed out in Section 4.2, luminance j.n.d.s do not play any very significant role in the present study.

The direction of the colour shifts shown in Fig. 5 are similar for all flesh tones i.e. in the green to blue-green direction as one proceeds, from the original colour, to that rendered by the System I phosphors, to the '69 – '70 current phosphors and finally to the '70 – '71 complementary shift phosphors. In most cases the magnitude of the shift is sufficiently small to be scarcely noticeable (although the direction of shift would not be acceptable if the magnitudes were greater). The shifts in the saturated colours are greater (Table 3) but cause less impairment to the observers.[3]

4.2. Cameras designed for NTSC, Netherlands Proposal and System I with display on '69 – '70 current phosphors (γ = 1)

There has been some reluctance on the part of Administrations to alter the specifications of the phosphor chromaticities from the original specification. The PAL System I phosphor chromaticities[1] are very close to those at present in use and those contemplated for use in the next year or two (Fig. 4). Nevertheless no one can be absolutely certain in which direction the chromaticities of new phosphors might move and some engineers might hope for a return to phosphors with chromaticities close to those of the original NTSC specification. As a possible compromise, there has been a Netherlands proposal[4] for chromaticities mid-way between those of the original NTSC phosphors and the current phosphors.

It is pertinent to enquire what would be the effect, on present receivers, of transmissions which are optimised for the NTSC and Netherlands set of phosphors. The introduction (Section 1) suggested that a mismatch was very undesirable but did not give quantitative results. It is the purpose of this Section to present quantitative results

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* and also conditions applying in matching textiles, spraying of large panels in the car industry and several other very practical conditions.

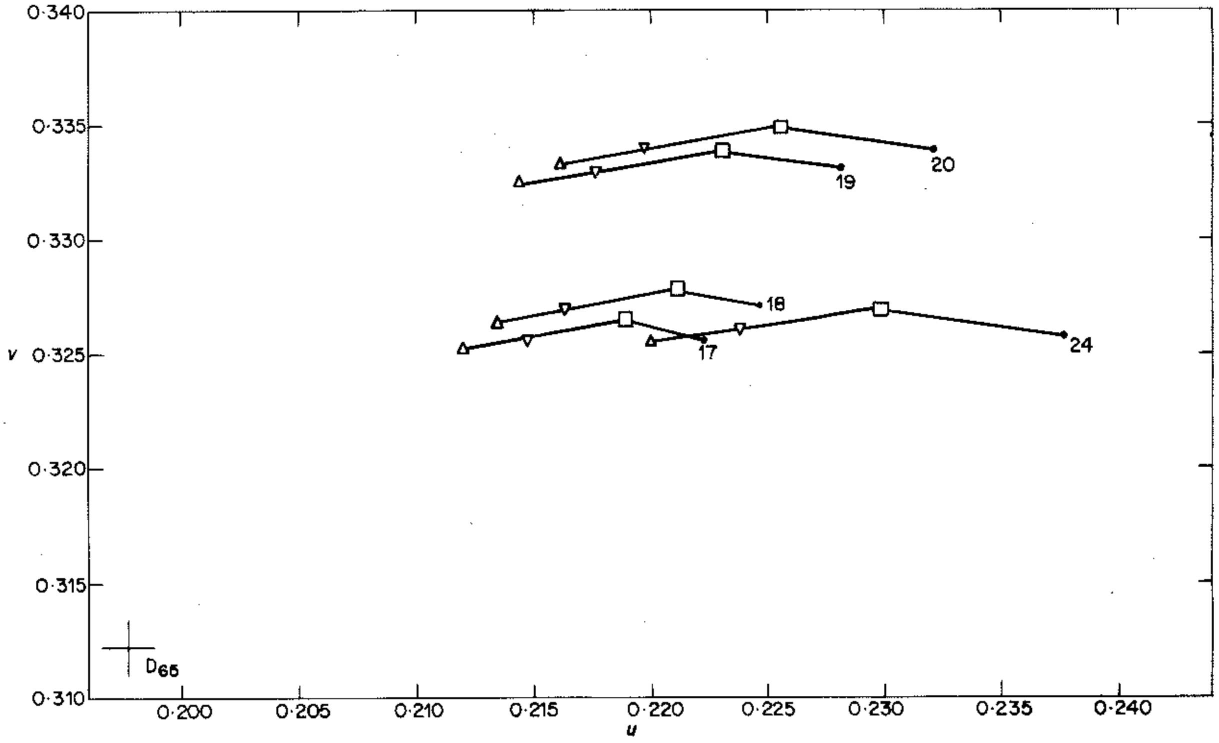

Fig. 6 - Reproduced chromaticities on current '69 — '70 display phosphors given by three cameras. $\gamma = 1$

● Original chromaticity ☐ Chromaticity given by camera designed for System I

Δ Chromaticity given by camera designed for NTSC ∇ Chromaticity given by camera designed for Netherlands Proposal

and these show that the effects are far from trivial. Table 4 summarises the results for the 26 test colours, sub-grouped as in Table 3.

TABLE 4

Pictures from Three Cameras Displayed on '69 – '70 Current Phosphors

	System I		Netherlands		NTSC	
	Chromaticity errors j.n.d.	Luminance errors j.n.d.	Chromaticity errors j.n.d.	Luminance errors j.n.d.	Chromaticity errors j.n.d.	Luminance errors j.n.d.
All Colours	4·1	1·7	5·8	1·6	6·7	1·6
Flesh Tones	1·6	0·3	3·0	0·3	3·8	0·3
Saturated Colours	8·0	3·7	10·6	3·4	12·0	3·0

At first sight it might appear that little harm has been done. For all colours the average colour error has increased from 4·1 for the System I camera to 6·7 j.n.d. for the NTSC camera (with the Netherlands proposal giving 5·8 j.n.d.). The most critical group, as previously mentioned, comprises the flesh tones and here there is an increase from 1·6 j.n.d. for the camera designed to suit System I to 3·8 j.n.d. for the NTSC camera (with the Netherlands proposal giving 3·0 j.n.d.). The direction of the changes (Fig. 6) is again in the green/blue-green direction, which is less accaptable than a change in the direction of red, and whereas the changes shown in Fig. 5 are sufficiently small not to matter unduly, those shown in Fig. 6 are too large to be ignored.

For saturated colours the increase from 8·0 j.n.d. (System I camera) to 12·0 j.n.d. (NTSC camera) is probably less troublesome because the correct colour relationships between the colours are maintained although the absolute accuracy leaves something to be desired.

Little mention has been made of the luminance errors so far. These seem to be fairly small, particularly for flesh tones, and more to the point, do not change appreciably with a change of camera design.

The results presented in this sub-section and the previous one (i.e. Sections 4.1 and 4.2) are probably of more significance for the theory of colour rendering in colour television than for its practice because of the assumption of an overall linear transfer characteristic ($\gamma = 1$). The effect of an overall transfer characteristic of index 1·26 will be given in Section 5 together with the results of subjective tests.[3]

5. Effects of mismatch between camera and display monitor ($\gamma = 1{\cdot}26$)

5.1. Camera designed for PAL System I: display on three sets of phosphors

There is strong experimental evidence[3] that the effects of mismatch are much more noticeable when the subject matter includes flesh tone as a reasonably large proportion of the total field. For this reason and in the interests of simplifying the presentation, Section 5 will be restricted to consideration of five typical flesh tones.

As in Section 4.1 a 3-tube camera designed for System I phosphors has been assumed and the reproductions on three monitors using different sets of phosphors have been computed. Fig. 7 shows the chromaticities of the reproductions when the overall gamma has an index of 1·26. A difficulty of interpretation of errors has to be considered. The reproduced chromaticities are now of higher chroma than the original, together with slight hue shifts. This enhancement of chroma (saturation) appears to be very acceptable to most viewers and it was in fact accepted in the parallel experimental study[3] that the reproduction of flesh tones on the System I monitor was very good. The five flesh tones used in the calculation were not identical with the models actually used in the test but are believed to be very typical of different types of Caucasian flesh tone. Table 5 gives the average calculated colorimetric shifts in j.n.d. units together with the average gradings given in the experimental trial.

TABLE 5

Phosphors	Computed Colour Difference from System I Display	EBU Scale I Gradings
System I	0	1·2
'69–'70 current	0·7	2·1
'70–'71 complementary shift	1·5	3·0

It will be observed that a change of 0·9 in EBU grading corresponds to 0·7 j.n.d. On this basis a change of 1 EBU grade corresponds to about 0·8 j.n.d.* The '70 –'71 complementary-shift phosphor produces a chromaticity shift (from the System I phosphor) of 1·5 j.n.d. and a change in EBU grading of 1·8 grades. Apart from giving some information as to the relevance of the j.n.d. scale, the subjective experiment is very important in its implications, viz. that under the condition of a camera designed for System I, the reproduction on present day phosphors is 'good' and that on the '70 – '71 complementary shift phosphors is 'fairly good' for the most critical subject matter and under conditions where a simultaneous comparison is made.

It will be noticed that, in the above discussion, the reference picture has been taken to be the one given by System I phosphors and not the original. This corresponds to the practical situation where the precise colouring and complexion of the subject is nearly always unknown: what is asked for is the appearance of reality, pleasantness and plausibility of picture. On these grounds it might be thought that relatively large errors could be tolerated, but this is not found to be true of flesh tones even though the preferred reproduction may not be an exact match to the original.

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* This is a specific example of the general point made in Section 4.1 that the j.n.d. unit used in this report is a relatively large one. Clearly the EBU quality scale gives a finer grading on flesh tones.

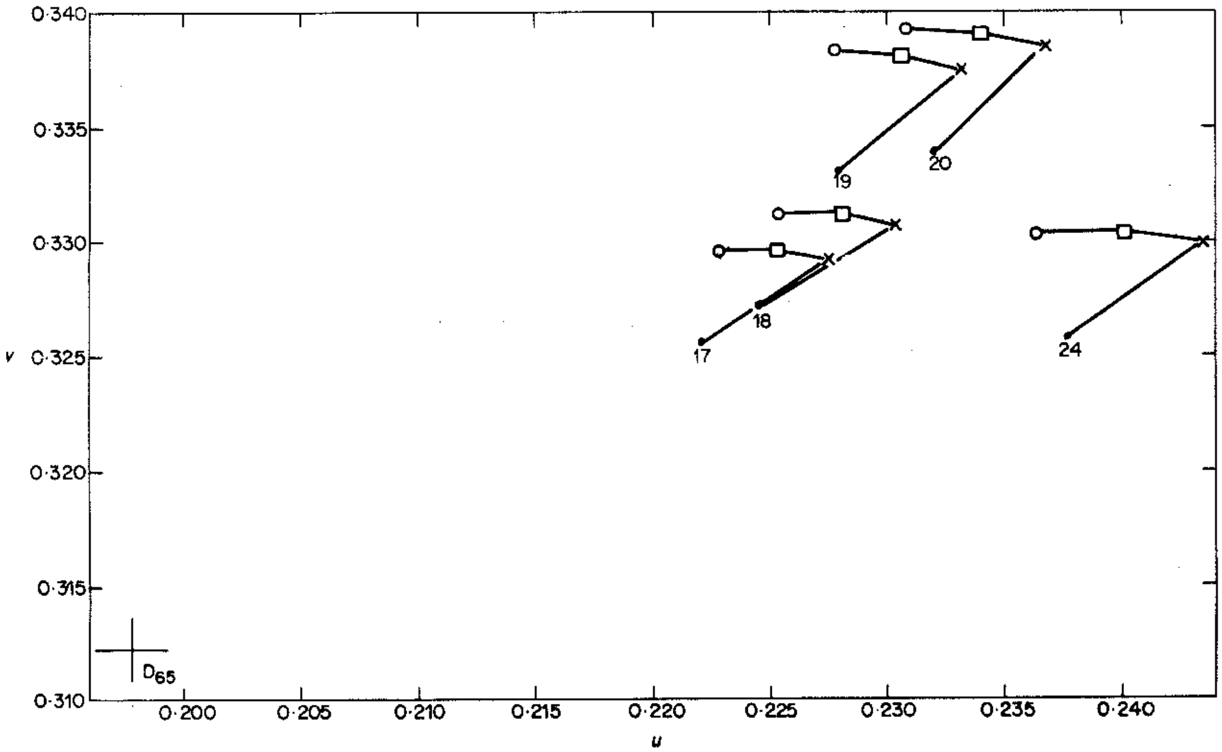

Fig. 7 - Camera designed for System I: Flesh tones (Nos. 17, 18, 19, 20 and 24) displayed on three sets of phosphors.
$\gamma = 1{\cdot}26$

● Original chromaticity X Chromaticity of System I display O Chromaticity of '70 – '71 complementary shift phosphor display
☐ Chromaticity of '69 – '70 current phosphor display

5.2. Cameras designed for NTSC, Netherlands Proposal and System I with display on '69 – '70 current phosphors ($\gamma = 1{\cdot}26$)

Following Section 4.2 the reproductions of the five chosen flesh tones have been evaluated when viewed by cameras adjusted to suit NTSC, Netherlands proposal and System I phosphors and replayed on one monitor, namely that using '69 – '70 current phosphors. The overall gamma is in excess of unity (1·26) and typical of modern television practice. Fig. 8 shows the computed chromaticities.

The 'System I camera' gives a result which is slightly oversaturated and with a hue shift (reference the original) in the yellow direction. These chromaticities are identical with the corresponding points of Fig. 7. Reference to Section 5.1 shows that, on average, this reproduction is 0·7 j.n.d. from the System I reproduction. This is a new starting point for the second set of subjective trials although it is now graded (on the EBU quality scale) on its merits with no implication that it ought to be regraded as grade 1; in fact it was graded at 1·9 (see Table 6). Fig. 8 shows that appreciably greater shifts of chromaticity are now involved, although the direction is very similar to that applying in Fig. 7. The average magnitude is given in Table 6 together with the results of the subjective tests.^{3} Whereas the changes of chromaticity produced by the different phosphors (Section 5.1) were such that the worst grading was 'fairly good', the situation with a change to an 'NTSC camera' gives a grading of 4·6 (this is between 'rather poor' and 'poor') and produces a change of 3·65 j.n.d.'s in an unfavourable direction i.e. green to blue-green.

TABLE 6

Camera Designed for	Computed Colour Difference ref. System I Display j.n.d.	Subjective Assessment EBU Scale I
System I	0·7	1·9
Netherlands proposal	2·55	4·3
NTSC	3·65	4·6

The Netherlands proposal is only slightly better on subjective grading, viz. 4·3: the computed colour error is 2·55 j.n.d. There is evidence of a non-linear relationship between objective chromaticity errors and subjective assessment, but this is clearly to be expected for the more gross chromaticity distortions. The relationship (using the camera designed for System I with the display on System I as the reference point) is shown in Fig. 9 and it would seem that a linear relationship applies up to about 2·5 j.n.d.'s of computed colour difference; for greater chromaticity errors the relationship 'flattens-out' but this is in a region where the subjective gradings are in the 'rather poor' to 'poor' classes between grades 4 and 5.

How bad the picture may be permitted to become is perhaps a matter for debate, but unless one is prepared to accept inferior standards of performance, the use of a camera designed either for NTSC phosphors or the Netherlands proposal is unacceptable with display tubes containing current phosphors.

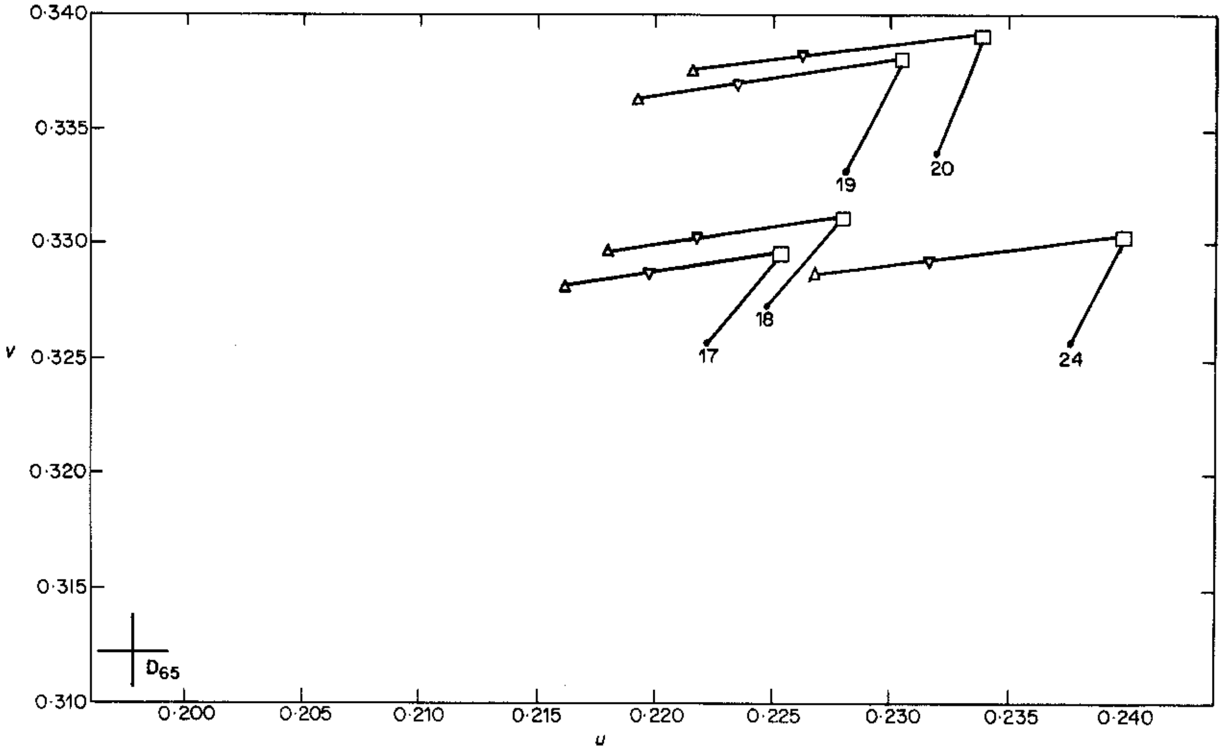

Fig. 8 - Reproduced chromaticities on current '69 – '70 display phosphors given by three cameras. $\gamma = 1{\cdot}26$

● Original chromaticity ☐ Chromaticity given by camera designed for System I

Δ Chromaticity given by camera designed for NTSC ∇ Chromaticity given by camera designed for Netherlands Proposal

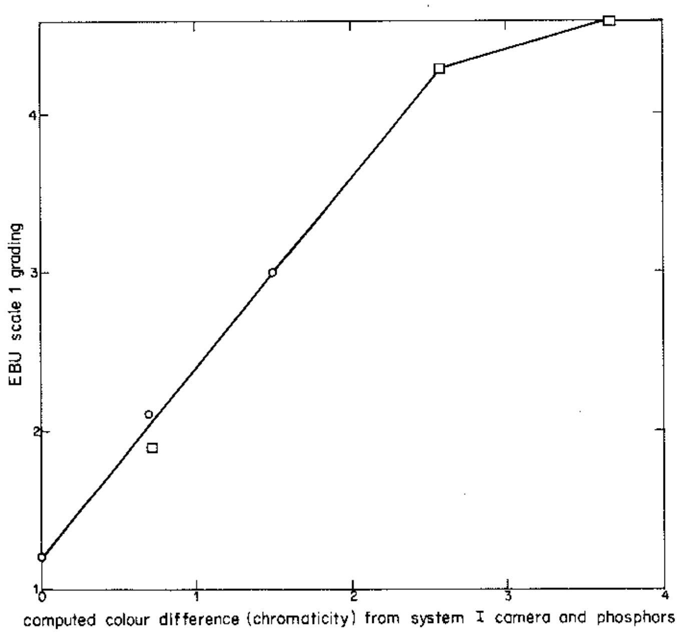

Fig. 9 - Flesh tones: relation between subjective and objective measurements. $\gamma = 1{\cdot}26$

○ Subjective test No. 1 □ Subjective test No. 2

6. Conclusions

Chromaticity errors have been evaluated both for a hypothetical system of unity gamma and for a practical system with a gamma of 1·26. In the latter case it has been shown that there is good correlation between the practical tests using the EBU quality scale and the average chromaticity shift computed for five flesh tones. It would appear that whereas the changes observed (and calculated) for a range of phosphors covering System I, '69 – '70 current phosphors and '70 – '71 complementary-shift phosphors is within reasonable bounds even under very critical test conditions and with critical subject matter, a change of camera analysis to suit the original NTSC phosphors produces unacceptable rendition of flesh tones on present day phosphors. The Netherlands proposal to choose chromaticities mid-way between NTSC phosphors and those of present day tubes does not substantially alter the subjective grading of the picture and is still unacceptable.

7. References

1. Characteristics of colour television systems. CCIR Doc. XI/1038-E, 13th November 1969.
2. 3 x 3 matrices for use with plumbicon colour cameras using three tubes. BBC Research Department Report No. PH-15, Serial No. 1967/59.
3. The choice of primary colour for colour television. BBC Research Department Report No. 1970/32.
4. CCIR Document XI/194. 3rd September 1969.

8. Appendix

A proposal has been made[3] that the errors produced by mismatch of the camera and the display phosphor could be substantially overcome by increasing the chroma gain. A theoretical investigation of this for test colour No. 19 (which has chromaticity shifts very close to the mean for the five selected flesh colours) has been undertaken and the result for an overall gamma of 1·26 is shown in Fig. 10. The chromaticity shift with reference to the System I display can clearly be altered by increasing the chroma gain but the error is never very small (minimum of 1·5 j.n.d.) and at this minimum point the hue error is in the green direction. If the chroma is further increased to 45% as determined in the practical trial[3] the hue error is probably less objectionable but the saturation has now appreciably exceeded that which is usually helpful in giving a more pleasant, 'larger-than-life' appearance. A further possibility is a change of relative *RGB* gains in the receiver (although few, if any, domestic receivers permit such an adjustment) to correct the flesh colour at the expense of the white-point balance. If this is applied to the picture with 45% excess chroma gain, the effect on the white-point is very considerable (4·2 j.n.d.'s in the blue direction) and it is thought that this shift of white point would affect the subjective appearance of all colours.

This theoretical study confirms the practical test with the 'NTSC camera': additionally it should be pointed out that these adjustments represent severe departures from an objective line-up procedure.

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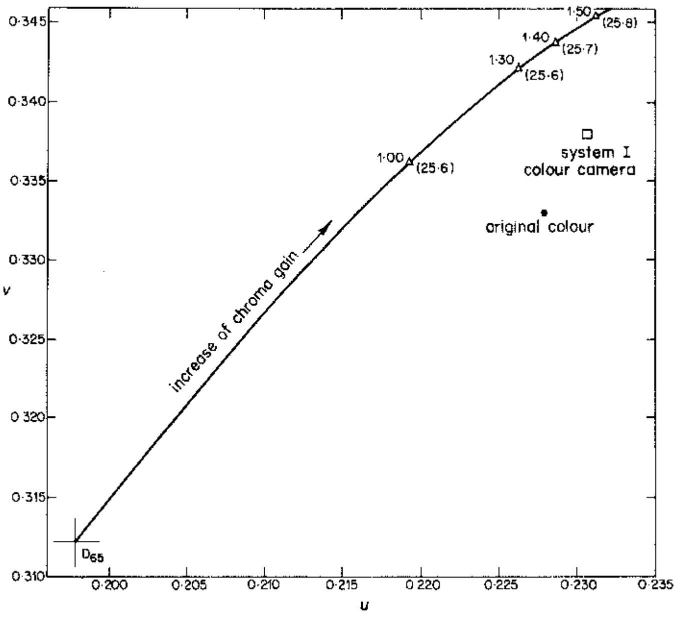

Fig. 10 - NTSC colour camera: effect of increase of chroma gain on flesh colour No. 19. $\gamma = 1{\cdot}26$

△ Chromaticity given by NTSC colour camera
The figure in brackets is the relative luminance
The figures 1·00, 1·30 etc. are the chrominance gains

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